

IMPLEMENTATION AND VALIDATION OF A COST-EFFECTIVE NETWORKED
RADAR-BASED HIGHWAY TRAFFIC SPEED MEASUREMENT SYSTEM

A Thesis

Presented in Partial Fulfillment of the Requirements for Graduation *with distinction* in
Electrical & Computer Engineering with the Bachelor of Science Degree from the
College of Engineering at The Ohio State University

By: Nathan E. Denning

The Ohio State University

2007

Thesis Review Committee:

Dr. Benjamin Coifman, Advisor

Dr. Ümit Özgüner

Abstract

Successful traffic management requires that there is reliable traffic speed information available for both research and decision-making purposes. Currently traffic monitoring is most commonly done with loop detectors, which are embedded into the roadway and can be used to detect the speed of a car passing over. Unfortunately, loop detectors are expensive, limiting the number of locations where they are cost-effective to use, and therefore restricting the total amount of traffic speed data that can be measured. Furthermore, they have a significant installation cost, potentially result in permanent damage to the roadway surface, and require that traffic lanes be closed in order to install which results in traveler delays.

This project consisted of the development of a cost-effective radar-based alternative to loop detector stations. It employs a bidirectional police radar connected to a server in the Ohio Department of Transportation's (ODOT) Columbus Traffic Management Center (TMC) via an existing fiber optic network. Analysis of the data obtained from the prototype radar unit as compared to data from the existing loop detector station demonstrates that a system of this type could be a suitable substitute for a loop detector in certain situations, and provides insight into the corrections required for reconciling radar data with loop detector data.

This Page Intentionally Left Blank

Acknowledgements

I would like to thank Dr. Benjamin Coifman for his continued work advising this research over the past 3 years. His knowledge and dedication were vital to ensuring the success of this project.

Furthermore, my sincere thanks to the College of Engineering at The Ohio State University for their generous financial support, allowing me to devote time to research as an undergraduate.

I would also like to acknowledge the Ohio Department of Transportation for their continued and generous support through the use of their equipment and network, as well as for their flexibility and cooperation in coordinating project logistics. Furthermore, I sincerely thank George Saylor and Matt Graf, both of the Ohio Department of Transportation, who were instrumental to the success of the project. George's creation of both the initial concept and much of the early software for the project was a major first step in developing the working system. Matt's help in establishing a networked connection and assisting with the initial placement and maintenance of the unit, as well as his willingness to travel on more than one occasion to the deployment site on short notice were all appreciated.

My thanks also go to my colleague on this project, Stephen Sawyer, whose knowledge of both software development and the Linux programming environment was crucial to the success of the project. Furthermore, I would like to thank Ho Lee for his help in locating loop detector summary data, without which, much of the data analysis would not have been possible.

I would also like to thank Kyle Walsh, whose skill with statistics, and uncanny ability to make it comprehensible, allowed for strong and concise conclusions to be drawn from the data.

Finally, I thank my parents, who have taught me to work hard and persevere, and who continue to be unflinching in their support of my endeavors.

Table of Contents

Abstract	ii
Acknowledgements	iv
List of Figures & Tables	vii
Introduction	1
Design Overview	4
Site Selection	8
Radar Unit Validation Overview	11
Sources of Radar Detector Errors & Discrepancies with Loop Detectors	12
Reconciling Radar Data with Concurrent Loop Data	17
Correcting for the Cosine Effect	18
Radar and Loop Data Comparison	25
Radar Effects on Traffic Speeds	29
Conclusions	33
References	35

List of Figures

Figure 1: Photograph of Ordinary Loop Detector Station	1
Figure 2: Photograph of MPH Industries, Inc. “Enforcer” Radar.....	4
Figure 3: Sample Output from ODOT Prototype	4
Figure 4: Pictorial Representation of Radar System.....	7
Figure 5: Aerial Photograph (with Added Callout) of I-71 Section Including Selected Site	9
Figure 6: Photograph of Radar Unit Deployed in Field.....	10
Figure 7: Uncorrected Radar & Loop Data Comparison (Samples from Mar. 18-19, ‘06).....	12
Figure 8: Diagram Depicting Cosine Effect	14
Figure 9: Effect of Radar Data Cosine Effect Correction (Samples from Mar. 25-30, ‘06)	19
Figure 10: Method One-Corrected Radar v. Loop Speeds (Samples from Mar. 25-30, ‘06)	21
Figure 11: Method One Difference Distributions (Samples from Mar. 25-30, ‘06).....	22
Figure 12: Method Two-Corrected Radar v. Loop Speeds (Samples from Mar. 25-30, ‘06)	23
Figure 13: Method Two Difference Distributions (Samples from Mar. 25-30, ‘06).....	24
Figure 14: Methods One & Two-Corrected Radar v. Loop Speeds (Samples from Mar. ‘06)	28
Figure 15: Loop Station V0007 Summary Data (December 2004 – March 2005).....	30
Figure 16: Comparison of Summary Data from Loop Station V0007 (Mar. ‘03, ‘04, ‘05)	31

List of Tables

Table 1: Comparison of Two Cosine Effect-Correction Methods.....	26
Table 2: Comparison of Two Cosine Effect-Correction Methods in Three Speed Ranges.....	27

Introduction

Reliable real-time traffic speed data is essential for the detection of freeway congestion, and, among other things, can be used to spot developing traffic problems, as well as provide predictive information to drivers who are planning routes. Furthermore, analysis of historical traffic data measurements allow for transportation officials to determine problematic periods and locations in order to make appropriate plans and budget allocations for increasing capacity at those times and positions¹.

Currently, the most common method for obtaining this type of traffic speed information is through the use of loop detectors. A loop detector consists of an inductive loop which is embedded into the roadway and connected to a detector and controller which is capable of calculating the speed of a car passing over the loop. A photograph showing a set of loops is provided as figure 1. The metal loop cabinet in the foreground



*Figure 1: Photograph of Ordinary Loop Detector Station
(Courtesy of Benjamin Coifman)*

is where the detector units are located, and these controller cabinets generally include an access point to a network which allows for real-time, or near real-time, loop data to be

sent to a central data processing center. In the case of this project, the Ohio Department of Transportation (ODOT) loop detector station that was used is connected via a fiber optic network to the ODOT Traffic Management Center (TMC) in downtown Columbus, Ohio.

Although loop detectors can be used to calculate several different types of information about traffic conditions², their use has substantial drawbacks. First, installing new loop detectors on existing roadways requires cutting into the pavement, necessitating that traffic lanes be closed, and resulting in permanent damage to the road surface. Furthermore, they have substantial initial and on-going costs³, and must be placed in each lane, meaning that the cost of any given station increases dramatically as the number of lanes increase.

For example, the loop station used for comparison in this project had a total of twelve loops, two in each of the six lanes, resulting in an estimated hardware cost³ of \$4500.00. This data also does not figure in either the direct cost of installation, or any additional losses to motorists as a result of the lanes being closed for installation. Furthermore, the annual cost to maintain those twelve loops is estimated³ at \$400.00. The high cost of loop stations, and the complex process by which they must be installed, means that their use must be limited to only the most essential location of the roadway network, significantly restricting the number of locations from which traffic that is available.

This project has considered whether a low-cost radar system can provide a suitable alternative to a loop detector station. The system employed in this project had an estimated cost⁴ of less than \$1500.00, meaning that approximately three such radar

systems could be purchased for the same price as a single twelve-loop station. In addition to the significantly lower purchase cost, and the almost negligible maintenance cost, radar offers several other advantages over loops. First, they can be installed with ease, without disrupting the flow of traffic or damaging the roadway surface. Furthermore, because the radar system measures data from all lanes simultaneously, the cost of the system does not increase with the number of lanes⁵, a stark contrast to loops. Additionally, the radar system has the potential to be redeployed if the need arises, whereas the loops are fixed in one location. Finally, although the radar system is similar to loop detectors insofar as it still requires a power source, the radar could be easily powered off of solar arrays and thus, does not require the same extensive infrastructure as loop detectors.

Design Overview

The prototype traffic speed measuring device designed and built for this project is based on earlier work done by George Saylor of ODOT. His design employed a bidirectional police radar, like the one shown in figure 2 (and identical to the one used on this project), to measure the speed of traffic traveling on Interstate 70 (I-70) in Columbus,



*Figure 2: Photograph of MPH Industries, Inc. “Enforcer” Radar
(Courtesy of MPH Industries, Inc.)*

Ohio, near Mound Street. The speed values measured by the radar were then overlaid onto live video footage, allowing for real-time monitoring, as shown in figure 3.



*Figure 3: Sample Output from ODOT Prototype
(Courtesy of George Saylor)*

Although George Saylor's project served as a good starting point for the subsequent research into using radar for real-time traffic monitoring, there remained a significant amount of work to be done before the method could be declared reliable, or recommended as a replacement for current loop methods. Perhaps the most critical improvement required was a means to collect and store aggregated radar data in order to analyze its correlation with expected values.

This project was conceived as an improvement to the system developed by George Saylor, and was undertaken with the goal of constructing a more rigorous proof of the viability of a radar-based traffic monitoring device. In order to determine how accurate the data obtained by a radar system was, it was necessary to install it in a location where it could be compared with data that was known to be accurate, e.g., a loop detector station. So the system was designed to be installed alongside an existing loop detector cabinet, which would yield concurrent radar and loop data. Because loop data is aggregated and stored every 30 seconds, at the beginning and 30-second marks of each minute, the radar system software was designed to collect measurements over those same sample periods and store the median value, in order to provide truly concurrent data for comparison. Further intricacies of the software are not discussed in this paper, given that the software was the subject of another thesis⁶.

The radar unit that was employed in this project is a Ka-band bidirectional police radar operating at a sampling frequency of approximately 4 Hz. Therefore, when the radar is operating at its ideal frequency, it returns 120 measurement samples from the two directions (both approaching and receding) in every 30-second sample period. The median of this data set is then computed and stored for later analysis.

Network Communication Path

The original plan for this project was that the radar be installed in the field along with a small controller and a computer that could store and aggregate data before sending it along the network to a centrally located data server. To that end, two different computers were procured, one of them a small single-board computer, designed for embedded applications, the other a laptop. The idea was that the computer located at the radar site could interface with the radar processor, aggregate a defined sample period of data, and then send it along the ODOT network to a central server at periodic intervals. This approach would have required the development of software that was capable of both interfacing with the radar's processor, as well additional software to handle the aggregated data transfers between the embedded computer and the central server.

A solution of this type was attempted, but suffered due to erratic performance from the embedded computer, and a lack of robustness due to the need for both the central server and the embedded computer to be restarted in the event of a broken connection. While these symptoms were due to specific hardware and design, the fact remained that it would have made long-term data analysis significantly more difficult, given that a field visit to restart the embedded machine would be required each time there was a connection problem. Ultimately it was determined that a much simpler solution existed for this proof of concept. Because the ODOT network that links the loop detectors (and therefore the radar, which would ultimately be connected into the ODOT network at loop cabinet V0007) to the TMC is not a standard computer network, but rather a fiber optic network using the RS-232 serial protocol, which happens to be the same protocol as the data that is output from the radar data processor, it was discovered

that the radar processor could plug directly into the fiber optic modems by means of a pin adapter. This solution is depicted in figure 4. At the TMC, the serial port on the central data server was simply connected directly into the fiber optic modem that was also

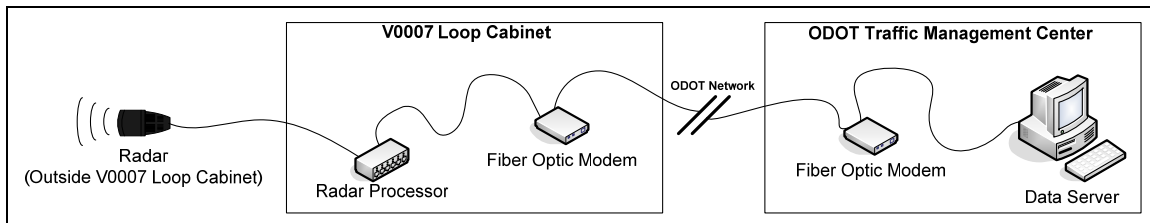


Figure 4: Pictorial Representation of Radar System

connected to the network. As a result, the radar processor could transmit data directly to the central server, all of which could be done without the need for an embedded computer, or any new network connection algorithms. In fact, from the perspective of the central data server, the radar was plugged directly into its serial port, meaning all it needed to do was record the values that were seen there.

Site Selection

There were several factors which were considered important in selection of a site to install the radar unit. First among these was that it was necessary to install the radar in a location where there was operational loop detector infrastructure. This infrastructure would allow for the comparison of data obtained from the radar with concurrent loop detector data that was known to be accurate. To that end, a station with dual loop detectors was the best choice, as they would likely provide extremely accurate and complete speed data with which to compare. Furthermore, the loop cabinet was necessary in order to power the radar unit in the field, and to serve as a network connection point, enabling the use of a remote server for data collection. It was crucial that the site had good freeway visibility in both directions of travel, fully enabling the system's bidirectional capabilities. This visibility was also necessary in order to truly test the radar's ability to successfully monitor multiple lanes.

Other important considerations included choosing a site that experienced heavy traffic on a regular basis, allowing for the verification of the system's ability to successfully detect freeway congestion. As well as selecting a site that would allow for easy access, should the system require maintenance.

Ultimately a location on Interstate 71 (I-71) in Columbus, Ohio between 17th Avenue and Hudson Street was chosen for the project. An aerial photograph of the site can be seen in figure 5. The site met each of the requirements discussed above, and with the exception of being located in the middle of an interstate curve, which had the potential to add complexity to the data sets and their subsequent analysis, was an ideal choice. The initial radar installation took place in the first months of 2005 and the entire

system was fully operational by March of that year. Figure 6 is a photograph of the location with the radar unit installed. Visible in the image, which was taken facing north

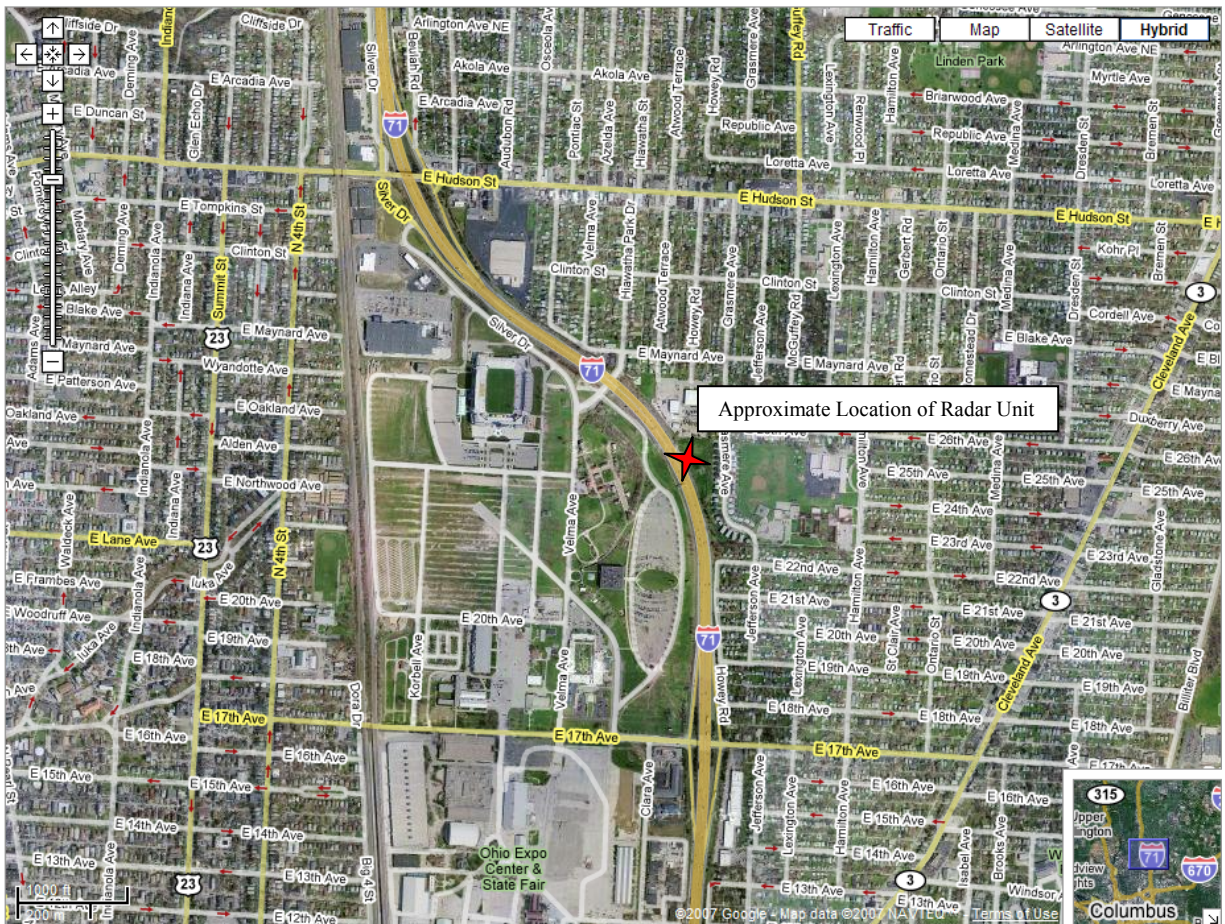
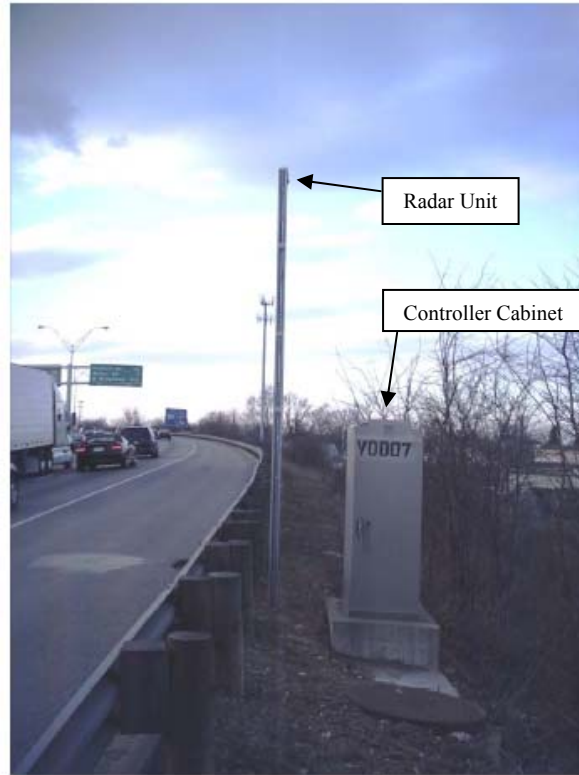


Figure 5: Aerial Photograph (with Added Callout) of I-71 Section Including Selected Site (Courtesy of Google Image)

on the northbound side of I-71, is the V0007 loop cabinet which provided the power supply and network connection for the radar unit. Also, the loops that are connected to this cabinet provided all of the concurrent data with which the comparison data analyses were done. The radar (visible in figure 6) is mounted on the pole to the immediate left of the cabinet and is facing away from the camera, directed at the I-71 center barrier wall

approximately 400 feet away from the loop cabinet. This target distance is sufficient for the radar's 13° cone to capture targets from all six freeway lanes (three in each direction). The radar was mounted as high as possible on the pole in order to increase the



*Figure 6: Photograph of Radar Unit Deployed in Field
(Courtesy of Steven Sawyer)*

visibility of all lanes to the radar, and to reduce the occurrence of vehicles nearer to the radar from blocking readings from more distant vehicles⁷. In this setup, southbound traffic is approaching the radar and northbound traffic is receding from the radar. The system operated successfully in this arrangement for a period of nearly one year, with few difficulties, and provided sufficient data for concept validation.

Radar Unit Validation Overview

In order to verify the proper operation of the radar unit it was necessary to compare the speeds recorded by the radar with the concurrent all-lane average speeds recorded by the loop detectors at station V0007. If the radar unit is to be considered as a suitable alternative for loop detector stations then it must be demonstrated that speeds recorded by the radar match speeds recorded by the loop detectors, within some reasonable tolerance. Because both the loop data and the radar data have been aggregated into 30-second increments (each day containing 2880 samples), beginning and ending concurrently, it was possible to perform this type of comparative analysis. Systematic errors were expected where the radar data would be off by a (roughly) constant scale factor due to the cosine effect. As turned out to always be the case in this project, it became necessary to adjust the radar data through the use of calculated correction factors. The next sections outline the process by which the data were compared and reconciled, as well as discuss other possible sources of less significant discrepancies for which no correction was made.

Sources of Radar Detector Errors & Discrepancies with Loop Detectors

As can be seen in figure 7, it is evident that the raw radar data does not closely match the concurrent uncorrected loop data. Also clear is that the shape of the radar data is very similar to that of the loop detector data, suggesting that the majority of the difference is due to the absence of an appropriate correction factor for the radar data. In

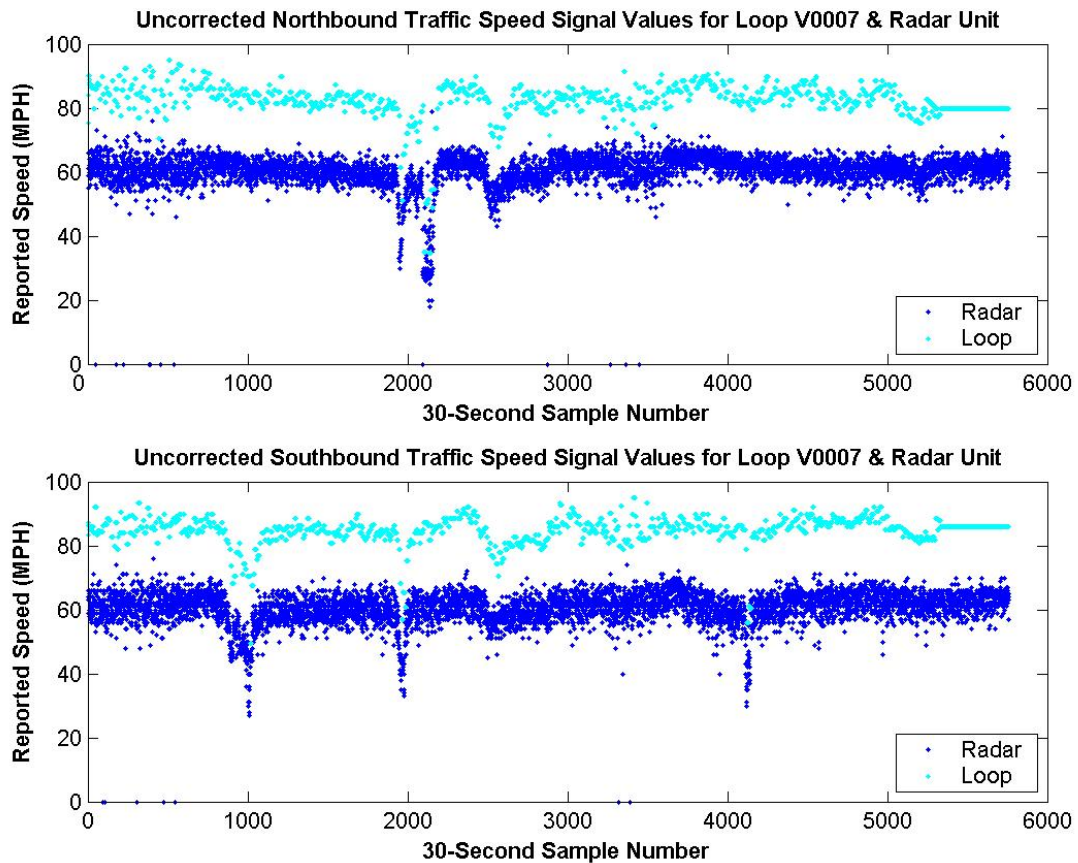


Figure 7: Uncorrected Radar & Loop Data Comparison (Samples from Mar. 18-19, '06)

fact, in the case of the loop detectors, the reported values are subsequently adjusted using a scale factor, given that most of the reported values are significantly higher than 80 MPH while the posted speed limit is 65 MPH. For the radar to be most efficiently

substituted into ODOT's current system, it would be ideal if the values reported by the radar closely matched with the values currently output by the loop detector. The goal therefore, is to account for any sources of significant error which may contribute to the discrepancy between the radar and the loop detector reported values. The three primary sources of this incongruity are a phenomenon called cosine effect, a changing angle between the cars and the radar (which essentially creates a variable cosine effect), and an unknown scale factor between the cosine-corrected radar data and the uncorrected loop data. Each of these is addressed in turn.

Cosine Effect & Changing Angles of Incidence

Perhaps the most significant source of error in the radar's measurement is the cosine effect. The effect is present whenever a measured vehicle moves along a path of travel that is not exactly in line with the axis of the radar's emitted radio wave, which, given that in practical situations it is almost never possible to locate a fixed radar unit directly in a vehicle's path, should be typical of every time a radar unit of this type is used. The error is a result of the fact that the radar is only capable of measuring the projection of the vehicle's velocity that is tangential to the direction the radar antenna is pointed. As a result of the difference between the direction of the radar antenna and the vehicle's path of travel, the measured speed is reduced by a factor of the cosine of the angle between those two axes, as shown in the schematic in figure 8. This figure depicts a situation similar to that experienced by the radar unit installed for this project. Because of the cosine effect, the radar would be unable to detect the true speed of the vehicles, and in the example of the tractor trailer depicted in the figure, the measured speed would be equal to $V_m = V_A \cdot \cos(\Theta_1)$, where V_A is the actual speed of the vehicle. Further

complicating the problem is the fact that for any one measurement the effect cannot simply be corrected by dividing the measured speed by the cosine of the known angle

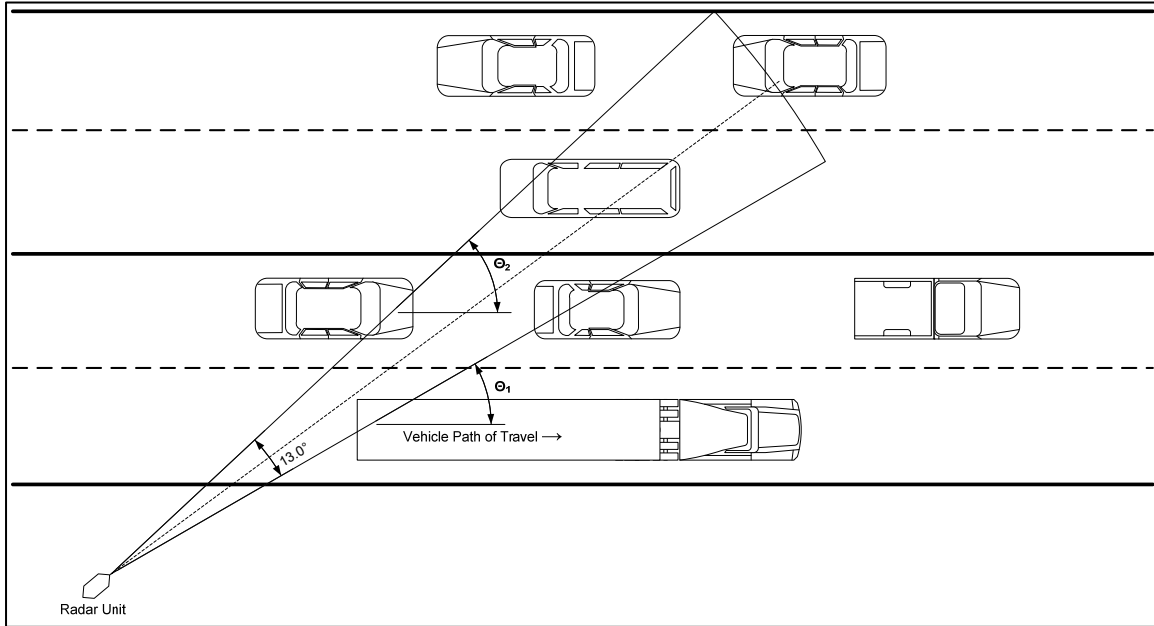


Figure 8: Diagram Depicting Cosine Effect

between the radar and the freeway for two reasons. First, the radar cone is 13° wide and so depending on which part of the road and radar cone a vehicle is traveling in, the angles will be different (note in the figure the difference between θ_1 and θ_2). Secondly, the radar detects only the speed of the most “salient” target, meaning that the location within the radar cone of a vehicle that is used to record a speed is not known. There is therefore no straightforward way to model or predict the precise angles at which vehicles are incident to the radar when their speeds are recorded. As a result, the measured speeds must be corrected in a different way.

Unknown Radar to Uncorrected Loop Scale Factor

The other significant source of discrepancy between the radar data and the uncorrected loop data exists because the loop detectors contain systemic inaccuracies which cause them to overstate speeds by about 25 MPH in clear traffic conditions. These reported speeds are then corrected by ODOT to more accurately represent true speeds. Because the goal of this project is to produce a system that works similarly to the existing loop detector system, it was not considered necessary or wise to attempt to correct the radar data to the uncorrected loop data, given that it would be adding in an inaccuracy that was not of the radar's making, and would ultimately require additional correction later to be made accurate. Instead, the radar data was compared only with concurrent corrected loop data in order to compute a single correction factor which would be considered the necessary correction for the cosine effect.

Other Possible Sources of Radar Error & Discrepancy

In addition to the sources of incongruity discussed above, there are at least two other known sources for which no adjustment has been made. The first is derived from the radar's physical location. Because it is mounted at the loop detector station and cannot be moved far for need of the station's power supply and network connection, the radar is not directly pointed at the traffic passing through the loop detectors. Rather, it is directed at traffic moving several hundred feet down the road from the loop detectors, meaning that the loop and radar data is not actually concurrent, strictly speaking. This discrepancy was considered to be a minor problem, however, given that the radar is located in a turn, where speeds are unlikely to vary in the short term, and also because the

data are aggregated in 30-second intervals, meaning that in free-flow, most cars are likely to pass through both the loop station and the radar cone within a few seconds.

Secondly, there is a fundamental difference in the way in which the radar operates as opposed to the loop detectors. For example, because the radar can be blocked from viewing distant southbound lanes by large vehicles in nearer northbound lanes, it occasionally reports no measurement for southbound speeds, even when the loops show fast-moving traffic. This situation demonstrates a real susceptibility in the system, which is impossible to predict or correct. The only solution to this problem would be to locate the radar unit in the center of the freeway, between the northbound and southbound lanes, making it significantly more difficult to access for both installation and maintenance purposes, or to add a radar unit to the other side of the road, guaranteeing bidirectional visibility, but doubling the site's cost. Finally, the radar counts values less than 15 MPH as 0 MPH, greatly reducing its capability in stop-and-go traffic.

Reconciling Radar Data with Concurrent Loop Data

After evaluating the possible sources of discrepancy, it was determined that the best methods for correction were those that only accounted for cosine effect. By computing an appropriate scale factor and using it to adjust the uncorrected radar data, the result could then be compared one-to-one with the concurrent corrected loop data, providing a picture of the system's accuracy, and therefore a prognosis on whether it can serve as a viable substitute for the loops. Given that the cosine effect is the most significant source of error, it was determined that this process would be an efficient, methodologically sound, and reasonably accurate method of reconciling the data from the two sources.

The unknown scale factor between the cosine-corrected radar and the uncorrected loop data (the third major source of error mentioned above) was not addressed, since again it made little sense to reconcile the radar data, which is only subject to the cosine effect, with uncorrected loop data, which has its own sources of inaccuracy.

Correcting for the Cosine Effect

Two methods for correcting error due to cosine effect are presented here. Both of these methods attempt to compute an appropriate correction scale factor between the uncorrected radar and the corrected loop data based on the analysis of historical differences between the two. It should be noted that reported values of 0 from the radar were excluded from the computations in each of the following methods as 0 values are used to denote the absence of radar targets rather than stopped traffic. Fortunately, both of the methods attempted are fairly straightforward, and the following analysis provides insight into the effectiveness of each.

Method One - Correcting by the Median Scale Factor

The first method involves aggregating data samples over a period of 30-seconds and computing their median in order to determine a “free-flow” (no congestion traffic conditions) scale factor. Computing the median of a 30-second sample in free-flow traffic provides an estimation of the “typical” car passing through the radar cone at a “typical” point in a “typical” part of the roadway during that particular time interval. Because the median value is not sensitive to outliers, cars that passed through the cone at extreme angles (yielding unusually high and low cosine effects) are excluded by the computation, resulting in a normalized set of speeds. These 30-second samples can then be compared to summary loop data in order to determine an appropriate scale factor for all of the 30-second samples, as well as to estimate the significance of the cosine effect in the measurements. In order to compare the summary loop data and the uncorrected radar data, each 30-second summary loop sample value (in MPH) for one month is divided by the concurrent 30-second radar median (in uncorrected MPH) for that same month. The

median of these quotients is then determined and chosen as the scale factor for the radar data for that month. Computing the median of all 30-second samples greatly reduces the significance of measurements that were taken during non-free-flow conditions. This process is done separately for both directions of travel, which allows for a larger scale factor for the side of the freeway opposite the radar installation. Figure 9 shows the effect of this calculation in reconciling a sample set of uncorrected radar data with its corresponding summary loop data. As can be seen in the figure, the selected method for cosine effect correction is extremely effective in readjusting the measured radar values to those obtained by the loop detectors, which are not subject to the phenomenon. In this

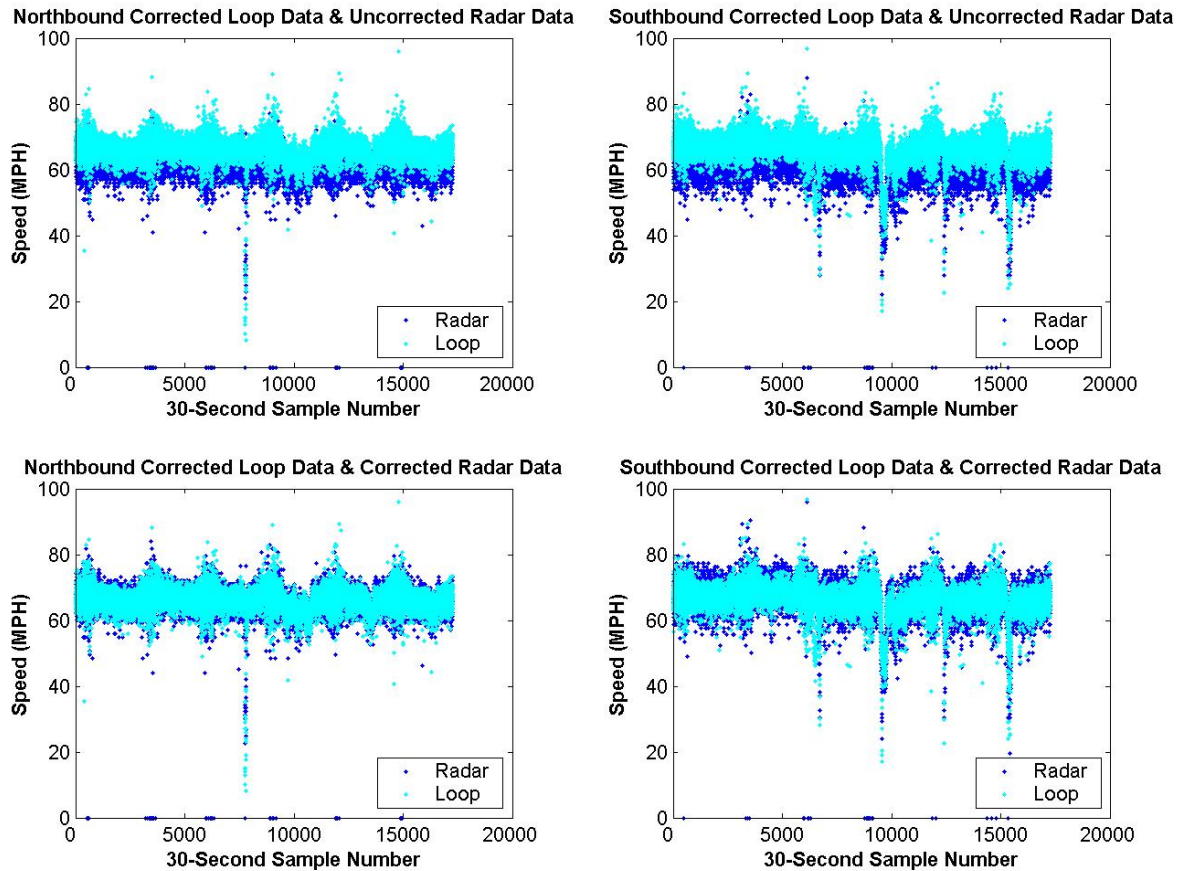


Figure 9: Effect of Radar Data Cosine Effect Correction (Samples from Mar. 25-30, '06)

case, the median scale factor required for reconciling the northbound data was 1.0761, while the median scale factor for the southbound data was 1.0895. It is again worth noting that it was not unexpected that the southbound data scale factor would be higher than that for the northbound data given the radar's positioning. Because the radar is located on the northbound side of the interstate, the cosine effect is less pronounced in the measurements of northbound data than it is in the southbound data.

From the computed scale factors it is possible to determine the typical impact of the cosine effect on the radar's measurements. By taking the inverse cosine of the reciprocal of each scale factor, we can determine the angle of incidence at which the median driver in each direction contacts the radar. In this case:

$$\Theta_{NB} = \cos^{-1}\left(\frac{1}{1.0761}\right) = 21.677^\circ$$

$$\Theta_{SB} = \cos^{-1}\left(\frac{1}{1.0895}\right) = 23.386^\circ$$

It is important to note that periodic adjustment of the scale factors is certainly recommended, and may even be required, due to such occurrences as the radar unit shifting position after installation.

Directly comparing the loop and radar values before and after correction for the cosine by method one yields the plots in figure 10. If the radar and loop detector reported exactly the same speed for every concurrent period, the points in the uncorrected plots of figure 10 would appear only on the diagonal line shown. Instead, the points are distributed around the line, and the top two plots show that the radar has a negative bias due to the cosine effect. The bottom two plots of figure 10 compare the loop and radar

data after the cosine correction factors obtained from the above method are applied to the radar data. It is clear from these plots that the correction factors move the distribution of the radar data closer to the ideal line, reducing the bias. The plots in figure 11 show the

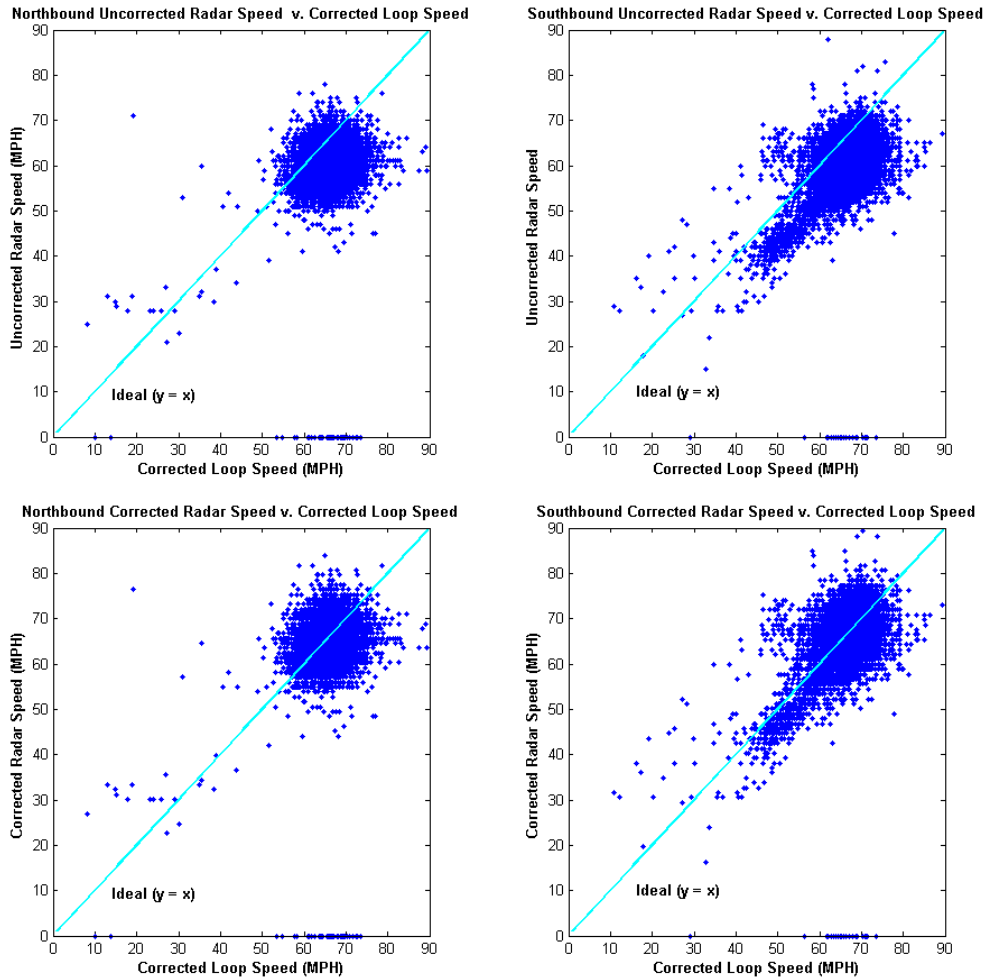


Figure 10: Method One-Corrected Radar v. Loop Speeds (Samples from Mar. 25-30, '06)

distribution of the differences between the corrected radar and corrected loop detector speeds. These plots show that the differences are approximately normally distributed around 0 and that the vast majority of radar values corrected by method one are between

± 5 MPH of the concurrent corrected loop speed. A quantitative analysis of this method compared to the second method appears in the next section.

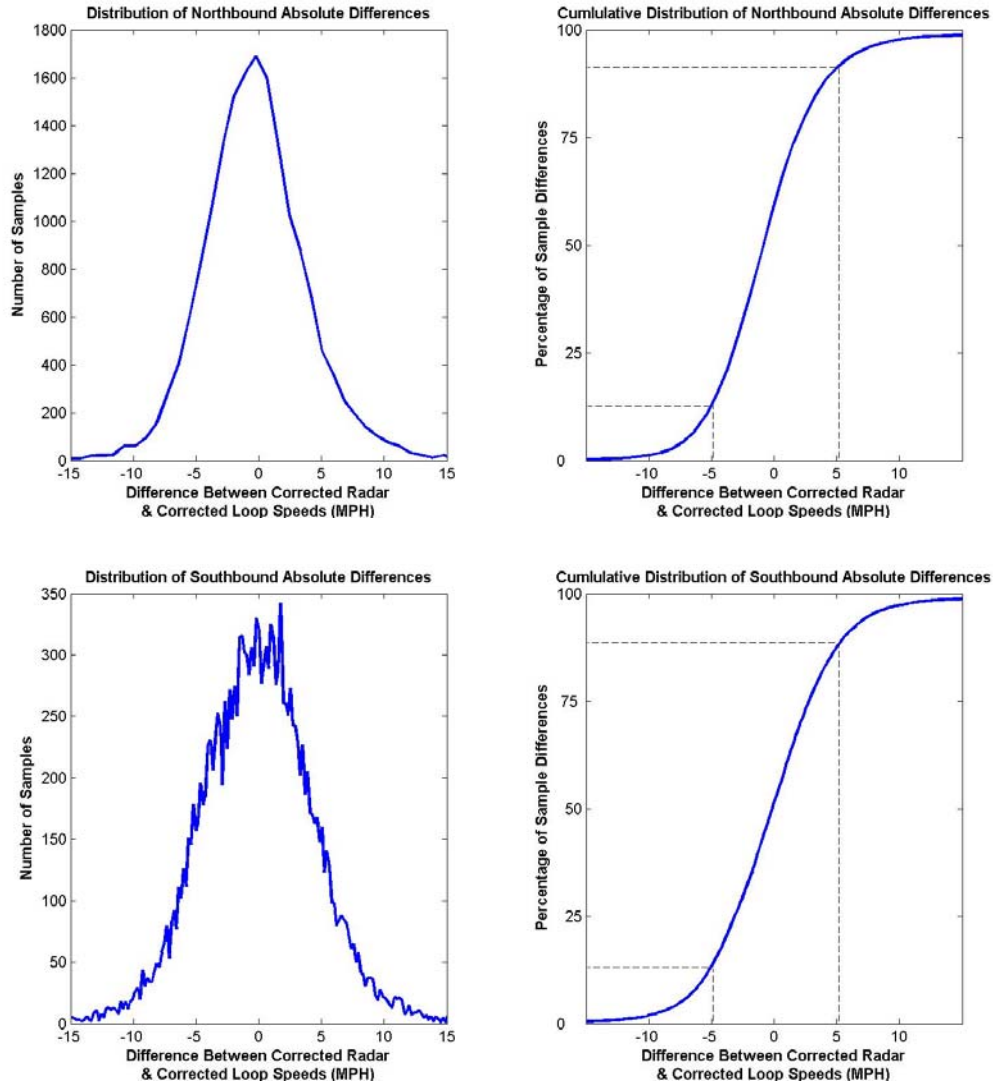
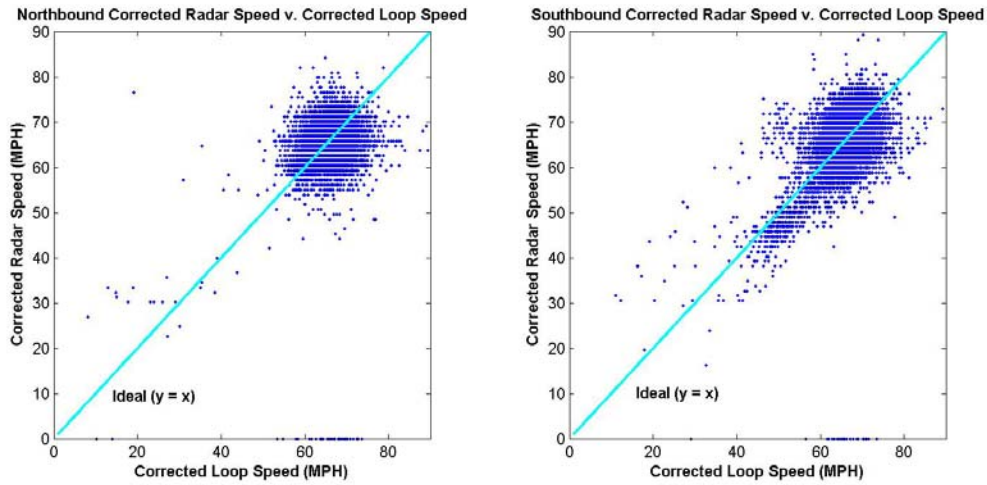


Figure 11: Method One Difference Distributions (Samples from Mar. 25-30, '06)

Method Two - Correcting the Average Difference to 0

The second method consists of taking the 30-second radar and corrected loop data aggregations and comparing them to determine the difference between each 30-second sample. The average of the difference is then computed and a scale factor is chosen

which makes the average difference equal to 0. Taking the average of the differences instead of the median increases the significance of outliers relative to the first method, however, it guarantees that the radar's values will have no bias compared to the loop detector. Again, this process is done separately for both directions of travel. Figure 12 shows the effect of this calculation in reconciling the same sample set of uncorrected



*Figure 12: Method Two-Corrected Radar v. Loop Speeds
(Samples from Mar. 25-30, '06)*

radar data with its corresponding summary loop data. As can be seen in the figure, this selected method for cosine effect correction is also extremely effective in readjusting the measured radar values to those obtained by the loop detectors. The average difference of the northbound data was approximately 4.85 MPH, yielding a scale factor of 1.07927 and an average angle of incidence of 22.096° , while the average difference of the southbound data was approximately 5.43 MPH, yielding a scale factor of 1.0893 and an average angle of incidence of 23.362° . It is worth noting that these scale factors are very similar to

those computed using method one. The plots in figure 13 show the distribution of the differences between the corrected radar and corrected loop detector speeds. These plots

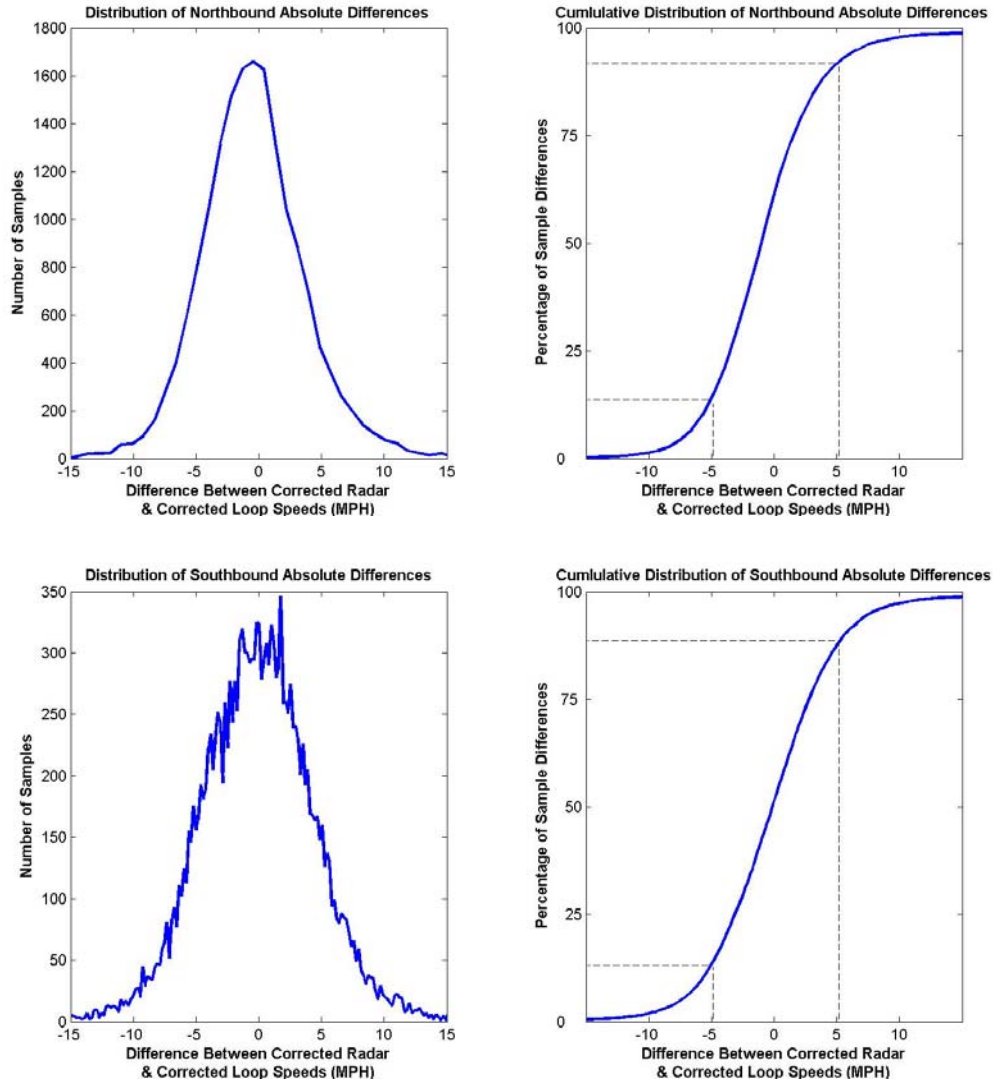


Figure 13: Method Two Difference Distributions (Samples from Mar. 25-30, '06)

show that the differences are again normally distributed around 0 and that the vast majority of radar values corrected by method one are between ± 5 MPH of the concurrent corrected loop detector values.

Radar and Loop Data Comparison

Building on the methods discussed in the previous section, extensive analysis was performed on the available concurrent radar and loop data in order to determine the effectiveness of the radar as a substitute for the loop detectors. This analysis consisted of using both described methods to perform cosine effect corrections on the nearly nine months of available radar data, and then comparing the results to the corresponding corrected loop signals in order to determine how closely the radar performed to the existing system.

Testing for Suitability of Radar as a Substitute for Loops

In order to properly compare the radar methods with the loop method, several suitable metrics for determining the differences between the methods were selected for calculation and review. This thesis considers the differences between the two methods in terms of bias, average absolute error, and average absolute percent error.

Bias was computed by determining the average signed difference between the corrected radar and corrected loop data. Average absolute error was computed as the average of the absolute differences between the corrected radar and corrected loop data. Average absolute percent error was computed by dividing the average absolute difference by the average loop detector speed. The results are as shown in table 1.

Northbound			
Method	Bias (MPH)	Average Absolute Error (MPH)	Average Absolute Percent Error (%)
One	0.36	3.34	5.06
Two	$\equiv 0$	3.35	5.07

Southbound			
Method	Bias (MPH)	Average Absolute Error (MPH)	Average Absolute Percent Error (%)
One	0.09	3.7	5.58
Two	$\equiv 0$	3.7	5.58

Table 1: Comparison of Two Cosine Effect-Correction Methods

From this comparison we can see that methods one and two are nearly identical in terms of bias, average absolute error and average absolute percent error. This similarity was not unexpected given that the correction factors obtained via these two methods were very similar.

It was also considered that the correction factors obtained by the two described methods performed with different effectiveness in different corrected loop speed ranges. It can be seen in figure 10 and in figure 12 that the corrected radar values are properly corrected in free-flow speeds (corrected loop speeds greater than 55 MPH), but are generally under-corrected in mild congestion (corrected loop speeds between 40 MPH and 55 MPH), and are poorly corrected in moderate to heavy congestion (corrected loop speeds less than 40 MPH). By computing the bias, average absolute error, and average absolute percent error for each of these three speed ranges it is possible to get a more complete picture of the effectiveness of the two presented correction methods and the performance of the radar in general. For this analysis, the corrected loop and uncorrected radar data were divided into three groups. Corrected loop speeds of less than 40 MPH were compared with the concurrent radar values in terms of bias, average absolute error

and average absolute percent error. The process was repeated for the corrected loop speed ranges of 40 MPH to 55 MPH and greater than 55 MPH. The results are as shown in table 2. As was expected from examining the corrected radar versus loop detector

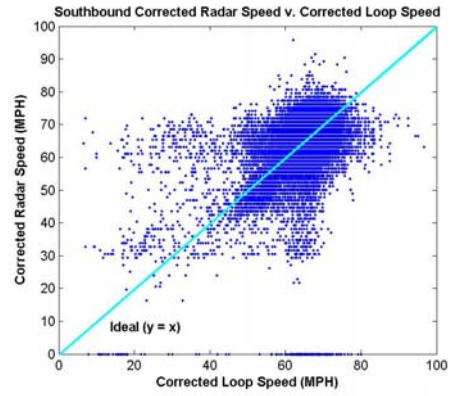
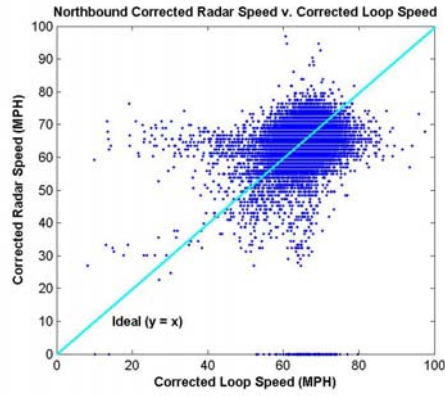
Method One									
Northbound					Southbound				
<i>Loop Speed (MPH)</i>	<i>Bias (MPH)</i>	<i>Average Absolute Error (MPH)</i>	<i>Average Absolute Percent Error (%)</i>	<i>Number of Samples</i>	<i>Loop Speed (MPH)</i>	<i>Bias (MPH)</i>	<i>Average Absolute Error (MPH)</i>	<i>Average Absolute Percent Error (%)</i>	<i>Number of Samples</i>
≥ 55	0.38	3.31	5.01	17086	≥ 55	0.13	3.62	5.41	16678
> 40 & < 55	-5.18	12.08	23.24	37	> 40 & < 55	-0.82	6.1	12.17	434
≤ 40	-8.96	12.86	53.22	22	≤ 40	-8.65	12.92	44.12	36

Method Two									
Northbound					Southbound				
<i>Loop Speed (MPH)</i>	<i>Bias (MPH)</i>	<i>Average Absolute Error (MPH)</i>	<i>Average Absolute Percent Error (%)</i>	<i>Number of Samples</i>	<i>Loop Speed (MPH)</i>	<i>Bias (MPH)</i>	<i>Average Absolute Error (MPH)</i>	<i>Average Absolute Percent Error (%)</i>	<i>Number of Samples</i>
≥ 55	0.19	3.32	5.02	17086	≥ 55	0.15	3.62	5.42	16678
> 40 & < 55	-5.35	12.22	23.51	37	> 40 & < 55	-0.81	6.1	12.17	434
≤ 40	-9.06	12.91	53.47	22	≤ 40	-8.64	12.91	44.11	36

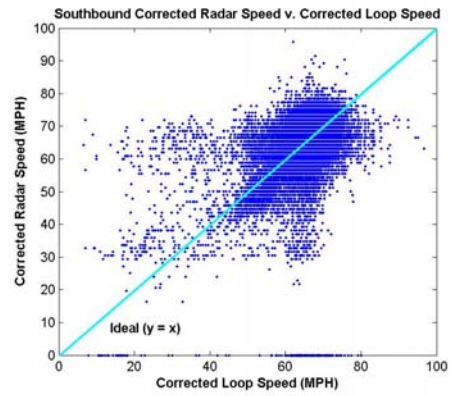
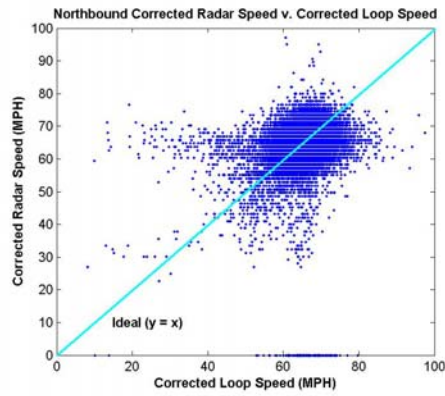
Table 2: Comparison of Two Cosine Effect-Correction Methods in Three Speed Ranges

plots for both method one and method two, the correction factors computed using the two methods work well for correcting free-flow traffic conditions, but perform increasingly poorly as the loop detector speeds decrease. This pattern becomes even more evident on the corrected radar versus loop detector comparison plots as the size of the sample is increased, and additional congestion conditions are included. Figure 14 shows the two correction methods applied to an entire month of data.

Method One



Method Two



*Figure 14: Methods One & Two-Corrected Radar v. Loop Speeds
(Samples from Mar. '06)*

Radar Effects on Traffic Speeds

In addition to the analysis comparing the radar's ability to measure values that closely match with the uncorrected loop values, it was also important to determine whether the presence of the radar had any significant impact on the speed of traffic. Because the radar unit can be detected by any off-the-shelf police radar detector, and is visible from the roadway, it was considered that there may be a slight reduction in the vehicle speeds after the installation of the radar, due to drivers being alerted to the presence of a speed-measuring device. In order to determine whether there had been a drop in the speed of traffic it was necessary to have data from a single source from both before and after the installation and operational dates. Therefore, V0007 loop detector summary data was collected for the purpose.

For this analysis, two data sets were used. The first consisted of data for the months of December 2004 through March 2005, a time period which contains both the date of the radar's initial installation and the date at which it became fully operational. The data could then be checked to see if there was a noticeable drop in speeds at the point where the radar was introduced. As can be seen in figure 15, there was no significant and consistent drop in speed during this time period which signifies that it is unlikely the radar had any significant effect on the speed of traffic.

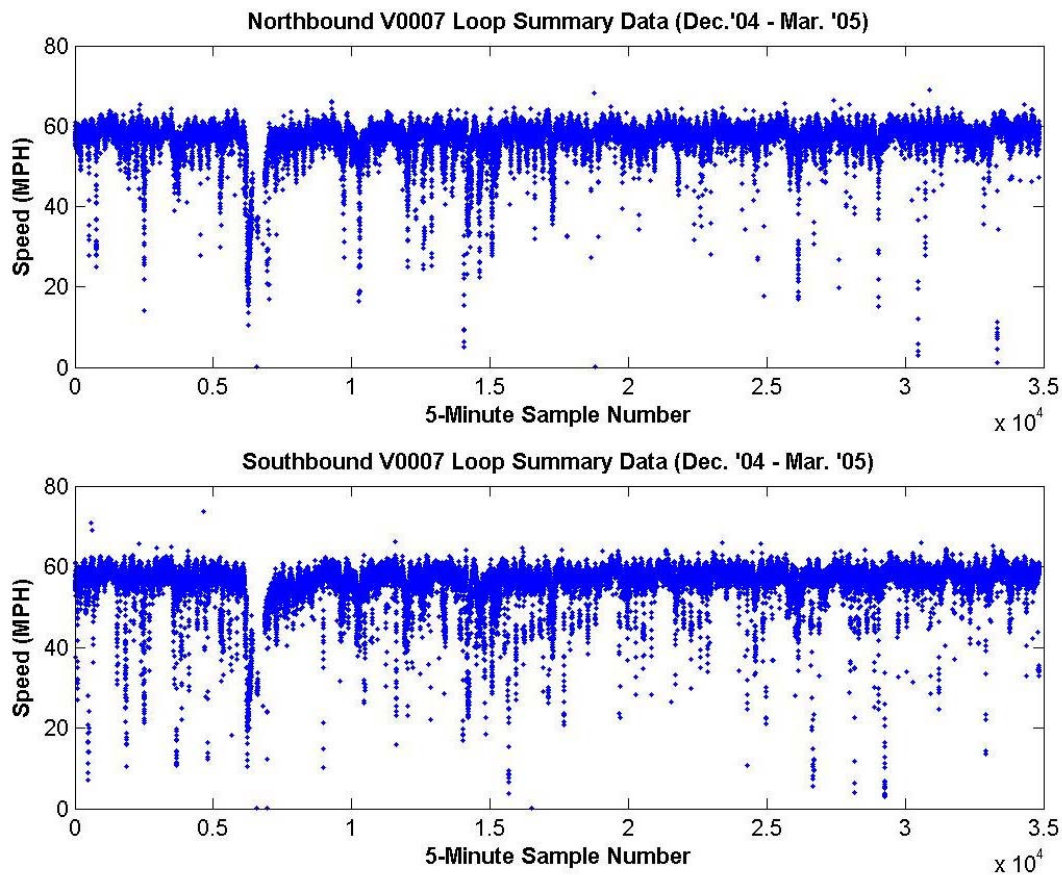


Figure 15: Loop Station V0007 Summary Data (December 2004 – March 2005)

The second data set was that for the month of March in the years 2003, 2004 and 2005. Because the radar was fully operational before March 2005, a comparison with the data from March in previous years would indicate whether traffic had slowed in March 2005, possibly as a result of the radar's installation. These data are shown in figure 16, plotted both as individual months and overlaid to provide easy comparison.

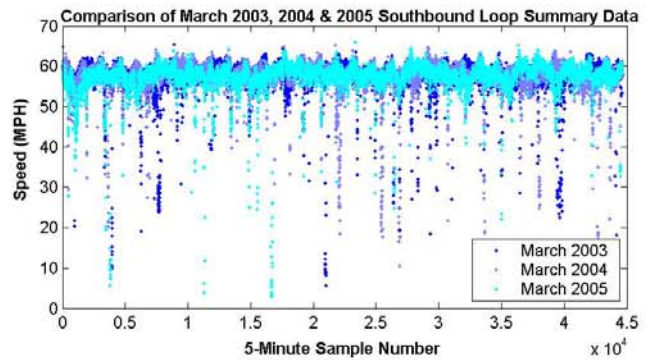
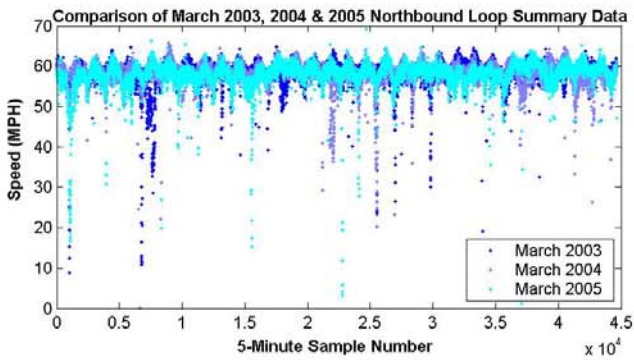
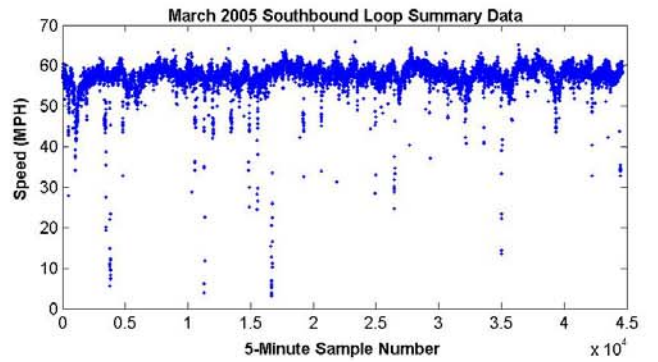
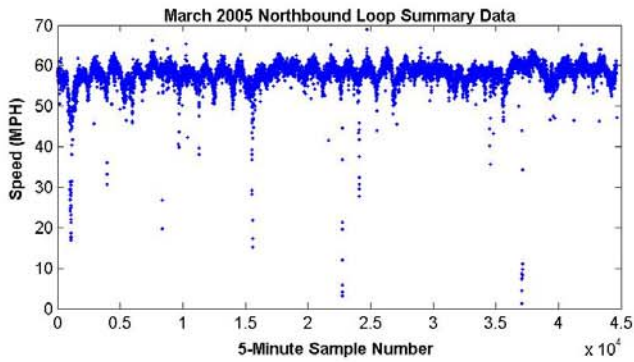
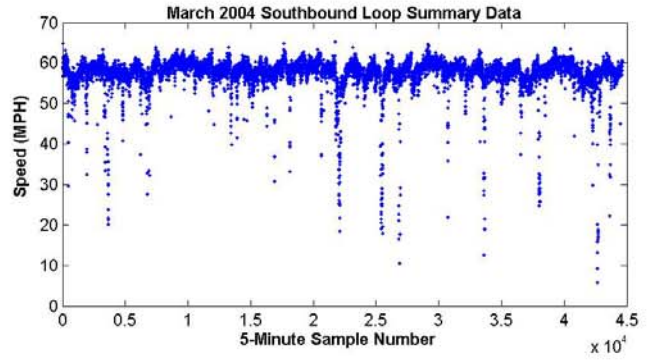
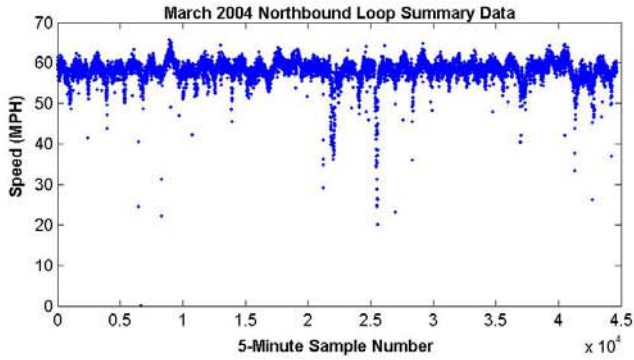
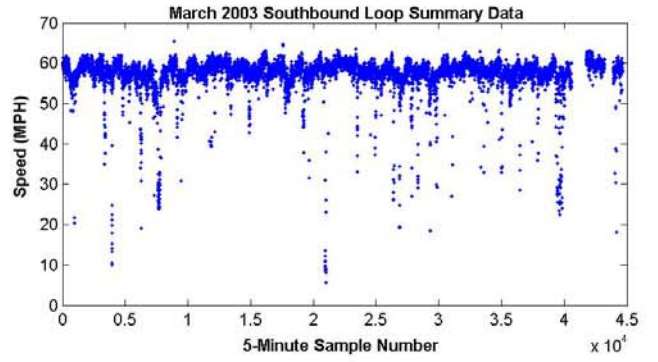
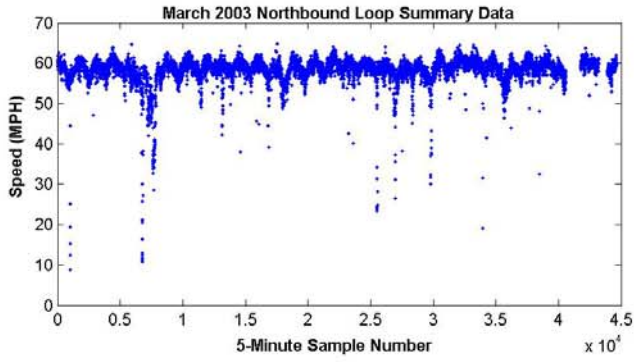


Figure 16: Comparison of Summary Data from Loop Station V0007 (Mar. '03, '04, '05)

As can be seen from the plots in figure 16, the speed data for the month of March is consistent from 2003 through 2005, indicating that the radar seems to have had a negligible, if any, effect on the speed of traffic at this location.

Conclusions

Based on the experience and data obtained in the course of this research, it is reasonable to say that a radar-based system similar to the one developed for this project can serve as a suitable alternative to loop detectors in certain situations. Although it was shown that there are distinct differences between the data obtained by the radar and the loop detectors due to an inherent difference in the methods, it was also shown that the effect of these differences on large data sets is very small. Additionally, there are numerous ways in which a system like this one might be improved in an effort to match the current methods even more closely. The use of multiple radars at a site, the relocation of the radar to the center of the freeway, and the improvement of correction algorithms would all contribute to making the system an even better substitute for loop detectors. Furthermore, the system has a demonstrated reliability, provides ease of installation, offers a reduced cost compared to loops, and has been shown to have a negligible, if any, effect on traffic speeds.

In addition, the cost difference between a radar system similar to the one employed in this project and a traditional loop detector station means that several radars could be deployed in different locations for the cost of a single loop detector station, allowing for a larger number of locations to be monitored for the same cost. Given the high level of scalability of a system like the one developed in this project, this savings seems to be one of its greatest advantages.

In spite of these benefits, there are still many good reasons to employ loop detectors. Loops provide additional traffic information that radars like the one used in this project cannot, such as flow, occupancy, and lane-specific speed data². Furthermore,

loops do not suffer from cosine effect or occlusion of distant lanes by closer vehicles.

That being said, there are many ways in which the system designed in this project could be refined and improved. The development of more sophisticated cosine correction algorithms could substantially improve the accuracy of such a system. Because all of the cosine correction algorithms explored in this paper involved scaling uncorrected radar speeds by a factor greater than 1, the resulting corrected data were spread more widely than the uncorrected speeds, making the radar data appear noisy. Algorithms which provide for an upward adjustment of the reported values while maintaining or even shrinking the spread of the data would make the radar data both more consistent and would reduce the average difference when compared with the concurrent loop detector data. All things being considered, this research has demonstrated the feasibility of a cost-effective radar-based traffic speed detector.

References

- [1] Neudorff, L; Randall, J; Reiss, R; Gordon, R (2003) “Freeway Management and Operations Handbook” Federal Highway Administration, Office of Transportation Management. *Report No. FHWA-OP-04-003*.
http://ops.fhwa.dot.gov/freewaymgmt/publications/frwy_mgmt_handbook/report_info.htm
- [2] Chen, C; Petty, K; Skabardonis, A; Varaiya, P; Jia, Z (2001) “Freeway Performance Measurement System: Mining Loop Detector Data” *Transportation Research Record, Issue 1748*, 96-102.
- [3] Carter, M; et al. (2000) “Metropolitan Model Deployment Initiative: San Antonio Evaluation Report” (Final Draft), Section 4.
<http://ntl.bts.gov/lib/9000/9700/9752/9xv01.pdf>
- [4] 2004, State of New York Revised Contract Award Notification – Traffic Speed Measurement Equipment (Statewide).
<http://wwwstage.ogs.state.ny.us/purchase/spg/pdfdocs/3820711537ra.pdf>
- [5] Gates, T; Schrock, S; Bonneson, J (2004) “Comparison of Portable Speed Measurement Devices” *Transportation Research Record, Issue 1870*, 139-146.
- [6] Sawyer, S (2006) “Development of the Necessary Software and Communication Pathway for a Cost-Effective Freeway Traffic Speed Measurement System” Undergraduate Thesis, The Ohio State University Department of Electrical & Computer Engineering.

- [7] Franklin, C (2005) “Practical Issues When Considering Non-Embedded Traffic Detection Technologies” *International Municipal Signal Association (IMSA) Journal, Vol. 43, Issue 3*.
- [8] LeBlanc, David (2004) *Statistics – Concepts and Applications for Science*, Jones and Bartlett Publishers, Boston. 183-202.